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ROTATING STALL INITIATION AND SUPPRESSION IN A CENTRIFUGAL FAN

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ABSTRACT

This paper presents results from an experiment designed to implement a control system to actively suppress a rotating stall condition in a centrifugal fan. The control system employed a circumferential array of twelve air injection jets located in the endwall of the fan. The system was not only able to suppress the eruption of a one-cell rotating stall condition in the fan during stall initiation, but was also capable of bringing the machine out of fully developed rotating stall. The controller was also capable of destabilizing the fan and accelerating the eruption of the first spatial mode.

INTRODUCTION

The operating range of a turbo-compressor is limited by the surge line on the system performance map. The surge line separates the regions of stable and unstable compressor operation. Designers must allow for a safety margin, known as the surge margin, which places the operating points for the compressor in a region far enough removed from the surge line so as to prevent the onset of instability.

The term "surge line" is somewhat misleading since surge is only one of two possible phenomena that can occur when this boundary is crossed. In turbomachinery compressors, the types of instabilities found can be categorized as rotating stall or surge. Surge refers to a global oscillation of the mass flow through the compression system, often with complete flow reversal occurring. Rotating stall, in contrast, is an instability local to the compressor itself, and is characterized by a circumferentially non-uniform mass deficit which propagates around the compressor annulus at a fraction of wheel speed. For low speed centrifugal compressors (i.e. centrifugal fans), rotating stall is the more commonly encountered unstable phenomena.

Research on rotating stall initiation and suppression has mainly been focused on compressors employed in aero-propulsion applications. In these high pressure ratio compressors, rotating stall can cause dangerous structural excitation and eventual destruction of the compressor. Machines of lower pressure rise, such as blowers and fans, can be operated safely for extended periods with rotating stall present. However, the performance reduction and noise generation associated with rotating stall make operation in this flow regime undesirable.

Because of the significant disadvantages of allowing a machine to operate with rotating stall present, techniques to extend the stable operating range of compressors have long been sought. Recently, methods of actively suppressing a rotating stall condition have been the focus of significant research activity. These methods typically employ a controlled circumferentially non-uniform inlet distortion, with the goal of suppressing an erupting rotating stall condition while still in its early stages. To date, success has been reported for low speed axial research compressors by authors by Day [1991] and by Paduano et al. [1991].

Rotating stall behavior is also encountered in centrifugal compressors, albeit with a much wider variety of stall cell number, speeds, and strengths than in axial machines [Fringe et al., 1984]. Experiments conducted by the authors on a low speed centrifugal compressor at Purdue University [Lawless and Fleeter, 1993b,c] have shown that the stalling process in that facility is characterized by an initially weak, spatially coherent disturbance that develops over a finite period of time into a rotating stall condition. This behavior was a key assumption in feasibility studies on the implementation of a rotating stall control system on a low speed centrifugal compressor made by the authors [Lawless and Fleeter, 1991, 1993a]. In these studies, the proposed control scheme involved the introduction of a weak inlet distortion in the form of a vorticity wave that was phased to adjust system stability and damp out the stall condition before it reached significant amplitude. The mathematical model that was developed predicted that significant range extension could be achieved by maintaining the control distortion within a given 'phase-window' to the erupting disturbance.

Based upon the information gained from the experimental investigation into the stalling behavior of the Purdue Low Speed Centrifugal Research Compressor (PLCRC), this paper presents results from an experiment designed to validate the conclusions drawn from the mathematical model for rotating stall control. The goal of the experiment is to implement a control system designed to address a single cell rotating stall condition, as this condition was previously observed to play a major role in the stalling process of the PLCRC.

EXPERIMENTAL FACILITY AND INSTRUMENTATION

Purdue Low Speed Centrifugal Research Compressor

The Purdue Low Speed Centrifugal Research Compressor (PLCRC), shown schematically in Figure 1, is a large scale facility that is employed to study flow phenomena typical of centrifugal compressors. With a maximum pressure ratio of 1.01, the PLCRC is more properly classified as a centrifugal fan, and therefore is ideally suited to investigate the instability phenomena of air movers of similar design. The PLCRC features a shrouded, mixed flow impeller with 23 back-swept blades, and a diffuser which may be configured with up to 30 cambered vanes. The impeller is driven by a 29.8 kW (40 H.P.) induction motor. The nominal operating speed for the impeller is 1790 rpm, giving an impeller pass frequency of 29.8 Hz and a blade pass frequency of 686.2 Hz.

The diffuser section of the PLCRC consists of a curved vaneless space and a vaned radial diffuser. The cambered diffuser vanes have a chord length of 16.5 cm (6.5 in.), and feature a NACA 4312 airfoil profile. As mentioned previously, the vanes are removable and can be adjusted for both stagger angle and leading edge radius.

Instrumentation

The PLCRC facility is instrumented with sensitive electret microphones connected to the flow by means of static pressure taps located on the O.D. endwall of the inlet section of the fan. Eight microphones are distributed uniformly around the inlet circumference 1.8 cm (0.7 in.) in front of the tip of the impeller leading edge. To prevent the high frequency signals from rotor blade passage and flow noise from dominating the low-frequency signals of interest, a short attenuator tube is installed between the microphones and the static taps in the fan endwall. The attenuator, consisting of a stainless steel tube of 4.5 mm diameter filled with a 5 mm long porous felt core, serves as a pneumatic low-pass filter. Each microphone with its specific attenuator tube is dynamically calibrated against an Entran EPIL-6B-2 dynamic pressure transducer. The characteristics of these microphones are given in detail by Lawless and Fleeter [1991b].

The quasi-steady performance of the machine under the influence of a control system is characterized by monitoring the fan mass through-flow and discharge scroll static pressure. These two parameters can then be presented in the form of the dynamic fan characteristic curve. In order to obtain dynamic pressure rise characteristic data while the fan is being throttled to a stall condition, the pressures across the orifice flow meter, the inlet total pressure, and the scroll pressure are recorded with four Scanivalve Model J Pressure Multiplexers. The throttle closure rate was kept to a value sufficiently low so that the frequency response of the Scanivalves was not exceeded.

Controlled Distortion Generation

An array of twenty-four fast acting solenoid control valves is employed to introduce a jet of air into the O.D. endwall of the fan inlet. The valves are used in pairs to deliver air from a distribution plenum regulated to a nominal gage pressure of 620 kPa (90 psig) to twelve air injection ports of 4.8 mm (3/16 inch) diameter located around the fan circumference. To accommodate the air injection ports, an extension of 17.8 cm (7 in.) in length is added to the fan inlet. As shown in Figure 2, the ports inject air at an angle of 30 degrees from the horizontal. The solenoid valves are of the miniature type, with a significant total pressure loss between the supply plenum and the air injection ports. A jet velocity of 60 m/s is achieved when discharging into ambient conditions, this value being four times the average inlet velocity to the fan at stall.

Two air valves are actuated at any given time in the inlet. Under steady air injection, this results in a mass flow addition to the fan inlet flow of less than two-tenths of one percent the mass flow through the fan just prior to stall. This can be compared to the mass flow deficit of a fully developed one-cell stall condition in this fan of approximately eight percent.

Control System

The control system consists of a Macintosh Quadra 950 microcomputer configured with two National Instruments NB-A2000 boards providing eight channels of simultaneous sampling analog to digital conversion. In addition, the computer is configured with a National Instruments NB-DMA2800 direct memory access board and a National Instruments NB-DIO-32F digital input/output board. The control valves are actuated with solid state relays activated by the logic state of a 12-bit word output from the digital input/output board. The twelve air injection jets are divided into six groups of two ports each, effectively dividing the fan annulus into 60 degree sectors. This

arrangement for propagating the control wave in 60 degree increments was chosen based on a favorable 'phase window' predicted from the mathematical model and the requirement to minimize cycle frequency for the control valves.

The feedback variable for the system is the first spatial mode of the endwall static pressure detected by the inlet microphone array. To improve the signal-to-noise ratio, the microphone signals are processed with analog biquad active amplifying filters. The filters are designed with a bandwidth of 10 Hz (based on a 3 dB cutoff) centered around the 24 Hz frequency expected for one-cell rotating stall. Since real-time scaling of the microphone signals would needlessly tax the control system, the filter gain is adjusted to match each microphones' response to a 24 Hz test pressure wave.

The control algorithm is based on a spatial Fourier transform of the signals from the filtered inlet microphone arrays in conjunction with the analog filters for each microphone channel. Continuous data acquisition of the inlet microphones at a sampling frequency of 5000 Hz is accomplished in the background. The most recent samples are fetched by the main processor of the Quadra 950 as required. The phase information from the spatial Fourier transform of the signal from the inlet microphones, with a specified control phase shift, is then employed to actuate the appropriate inlet control valves.

Data Acquisition and Analysis

In order to monitor the stall event, a second Macintosh Quadra 950 computer equipped with three National Instruments NB-A2000 boards providing twelve channels of simultaneous sampling analog to digital conversion is employed. This allows raw microphone signals as well as performance data to be acquired independently of the computer implementing the control.

Analysis techniques employed on the signals from the inlet microphone array are identical to that described for the stall initiation characterization described by Lawless and Fleeter [1993]. Data from the microphones are numerically band-pass filtered using Butterworth filtering algorithms. After filtering, the signals for each microphone are scaled by the appropriate gain value and then processed with a spatial Fourier transform. The results of this transform separates the signal into spatial Fourier components, known as spatial modes. These spatial modes are the spatial-domain equivalent of the harmonics obtained from a temporal-domain transform, the mode number representing the number of disturbance wavelengths around the machine circumference. Hence, the fundamental mode for a one-cell stall condition will be the first mode, and that for a two-cell stall condition is the second mode.

During throttle down to a stall condition, the pressures across the orifice plate, the inlet total pressure, and the discharge scroll pressure are monitored with the Scanivalve pressure transducers. Since the fan is throttled down slowly, these readings were able to accurately track flow coefficient and pressure coefficient.

RESULTS

Active Control of Rotating Stall

The control system was evaluated on the fan with 30 diffuser vanes at 70 degrees stagger. This configuration was of interest because of the observed eruption of both one-cell and three-cell stall conditions during stall initiation. If successful suppression of the one-cell condition was achieved, the role of the three-cell condition in the stalling process could be clarified.

The results presented in Figure 3 shows the rise of the first and third spatial modes as the fan is throttled down into a stall condition without any intervention by the control system. This figure shows a trace of the magnitude of the given spatial mode with time as the fan enters a stall condition. It can be seen in this figure that the first spatial mode, which represents a developing one-cell stall condition, erupts first. After the throttle down continues, the first mode decays as a mode three disturbance (representing a three-cell stall condition) begins to dominate the fan flow pattern.

The results of implementing the control system at a stabilizing phase angle are presented in Figure 4. Here, as the fan is throttled to the stall condition the control system seeks the eruption of first mode waves and actuates the inlet jets accordingly. As seen by comparison with the case where no control is used, the control system suppresses the eruption of the first spatial mode and holds this mode to a level substantially reduced from that which occurs with the natural stalling process. However, with the successful suppression of the first spatial mode, the third mode erupts and now dominates the stalling behavior.

The operating range extension achieved with the successful control of the first mode is shown in Figure 5. The stalling points for the fan represented in the previous figures are illustrated on a cubic curve fit to the steady fan

characteristic. Three cases are presented, that for the control introduced at a stabilizing phase angle, control introduced at a destabilizing phase angle, and the case of inactive control. The early stall of the fan under the influence of destabilizing control is clearly shown. When the stabilizing controller is implemented, the net effect is to change the mode of the instability, with only a slight change in the flow coefficient at stall. This behavior was not unexpected, as for this fan build the three-cell stall condition was one of the normally occurring dominate modes. To illustrate the effect of the control system on a fan build where the three-cell stall condition was normally not present, the fan was re-configured with 15 vanes set at 70 degrees stagger. As shown in Figure 6, the control system clearly extended the stable operating range of the fan. When stall did occur it was again in a three-cell pattern, which was a condition not seen in the natural stalling behavior for this build.

The effect of the stall control system on the fan when already in one-cell rotating stall is presented in the next figure. The fan was throttled slowly until the fan entered one cell rotating stall, and then the throttle motion was stopped. Figure 7 shows the trace from a single inlet microphone filtered with the analog bandpass filter. The region of stabilizing control activity is shown at the top of the figure. The rise and decay of the one-cell stall condition is clearly shown, with a significant reduction in the pressure signal in the frequency band associated with this stall condition. The ability of the control system to bring the fan out of fully developed rotating stalling stall was somewhat suppressing given the limited control authority of the air jets. This ability suggests that even small inlet distortions can result in favorable damping characteristics for a given mode.

SUMMARY AND CONCLUSIONS

The active control of first mode rotating stall has been successfully demonstrated for a centrifugal fan. The stall control was implemented by the introduction of a phased inlet distortion. This distortion was introduced by an array of twelve air injection ports located in the inlet O.D. endwall.

The control system was not only able to suppress the eruption of the first mode in the fan during stall initiation, but was also capable of bringing the machine out of fully developed rotating stall. The controller was also capable of destabilizing the fan and accelerating the eruption of the first spatial mode.

In the case investigated, the stall control system provides only slight increases in stall margin. This was due to the fact that with the successful suppression of the first spatial mode, higher instability modes are excited and develop into a higher order stall condition. In addition, the fan exhibited a surge condition that was dependent on the suppression of the one-cell stall condition.

The size of the control mass addition dismisses any argument that this mass injection is compensating for the mass deficit exhibited in fully developed rotating stall. In particular, the mass addition under steady blowing was less than two tenths of one percent of the mass through-flow of the fan prior to stall, whereas the mass deficit in rotating stall was roughly eight percent of the mass flow through the fan prior to stall. Therefore, under steady blowing, the mass introduced by the air jets was smaller by a factor of at least forty than the mass flow deficit in rotating stall. In actual application, the jets were pulsed at a frequency of 144 Hz (six sectors around the annulus tracking a 24 Hz wave), which further reduced the mass addition.

In conclusion, the practical application of control systems such as that demonstrated here requires further study into the control of multiple spatial modes and cost effective control and actuation systems. If this could be achieved, continued operation beyond the surge line could be achieved without the noise generation and reduced delivery pressure that are associated with the occurrence of rotating stall. This would allow an air delivery system to be designed with greater tolerance to transients from a mean operating condition.

REFERENCES

- Day, I.J., "Active Suppression of Rotating Stall and Surge in Axial Compressors," ASME Paper 91-GT-87, 1991.
- Frigne, P., and Van Den Braembussche, R., "Distinction Between Different Types of Impeller and Diffuser Rotating Stall in a Centrifugal Compressor With Vaneless Diffuser," *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 106, April, 1984, pp. 468-474.
- Lawless, P.B. and Fleeter, S. "Active Unsteady Aerodynamic Suppression of Rotating Stall in an Incompressible Flow Centrifugal Compressor with Vaned Diffuser," AIAA Paper 91-1898, June 1991.
- Lawless, P.B. and Fleeter, S. "Prediction of Active Control of Subsonic Centrifugal Compressor Rotating Stall," AIAA Paper 93-0153, January 1993a.
- Lawless, P.B., and Fleeter, S. "Rotating Stall Acoustic Signature in a Low Speed Centrifugal Compressor Part I: Vaneless Diffuser" ASME Paper 93-GT-297, May 1993b.
- Lawless, P.B., and Fleeter, S. "Rotating Stall Acoustic Signature in a Low Speed Centrifugal Compressor Part II: Vaned Diffuser" ASME Paper 93-GT-254, May 1993c.

Paduano, J., Epstein, A.H., Valavani, L., Longley, J.P., Greitzer, E.M., and Guenette, G.R., "Active Control of Rotating Stall in a Low Speed Axial Compressor," ASME Paper 91-GT-88, 1991.

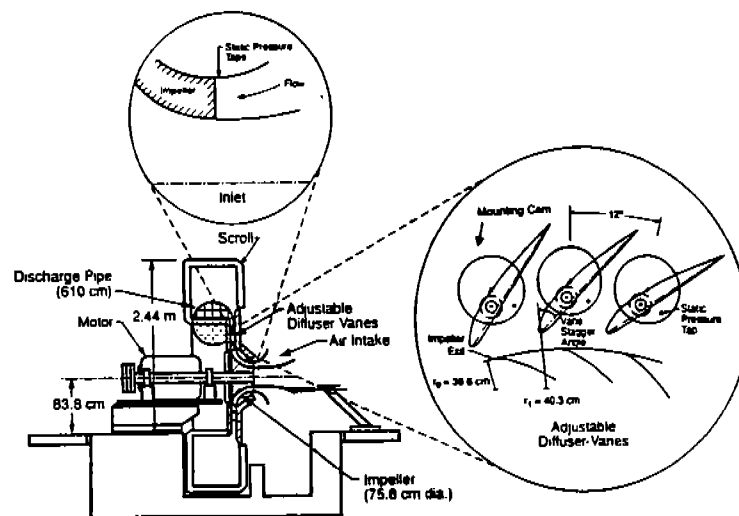


Figure 1. The PLRCC Facility.

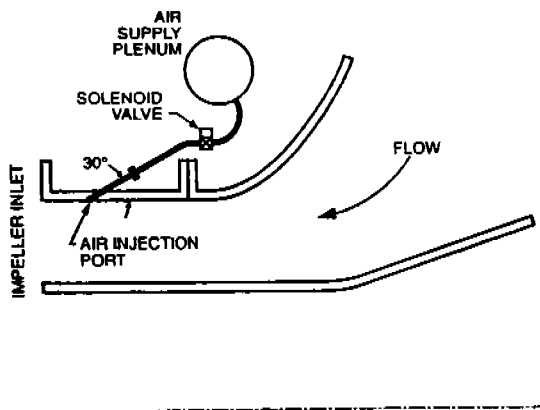


Figure 2. Extended compressor inlet showing air injection ports.

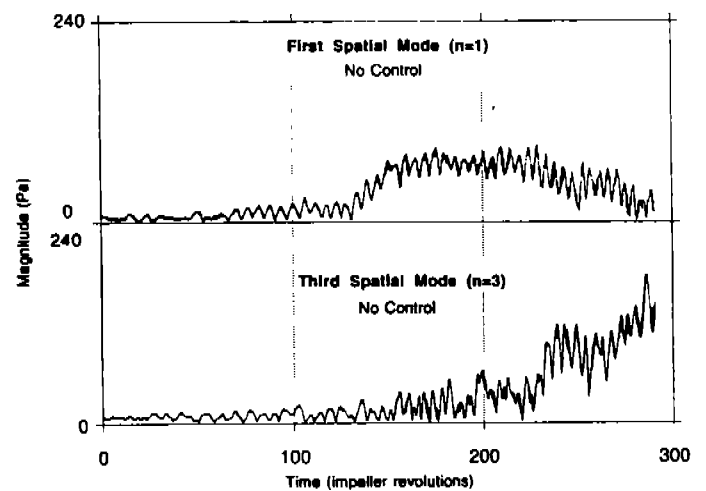


Figure 3. Rise of the first and third spatial modes. Normal stalling behavior.

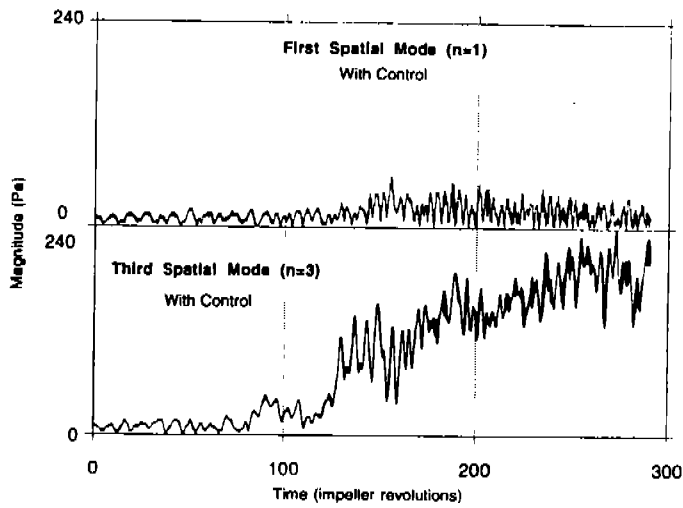


Figure 4. Effect of the control on the rise of the first and third spatial modes.

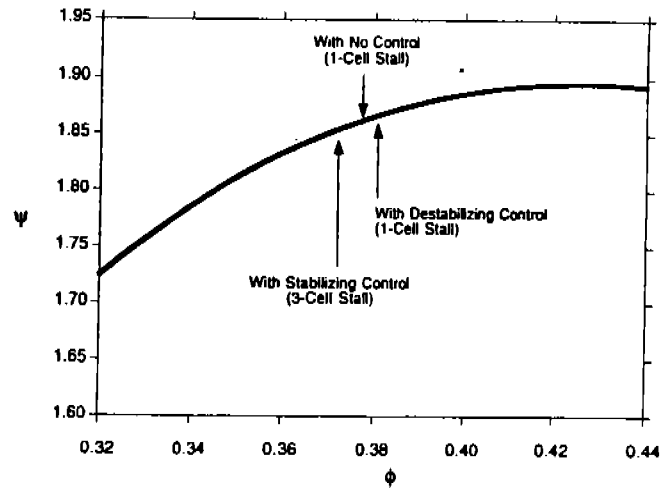


Figure 6. Location of fully developed stall on the system characteristic (15 Vanes).

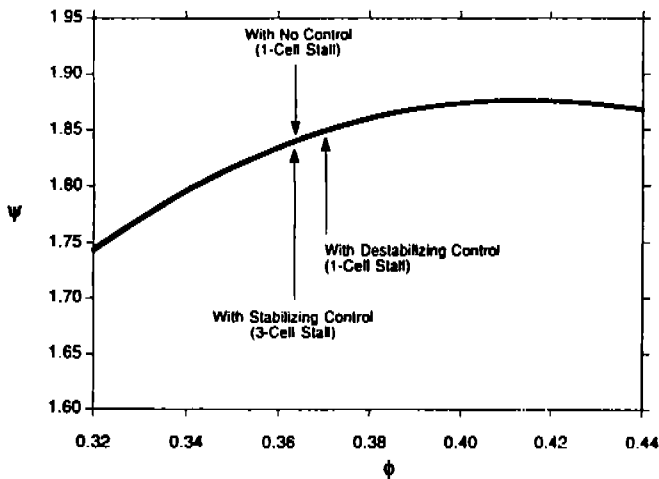


Figure 5. Location of fully developed stall on the system characteristic (30 Vanes).

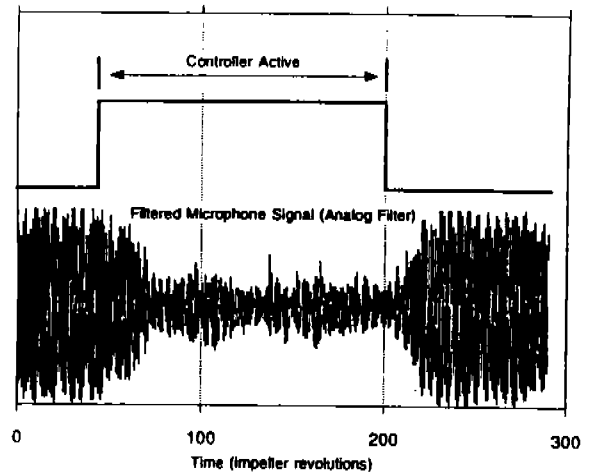


Figure 7. Effect of introducing stabilizing control on the compressor in rotating stall.